Winter 1994 Weather and Ice Conditions for the Laurentian Great Lakes*

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ABSTRACT

The Laurentian Great Lakes developed their most extensive ice cover in over a decade during winter 1994 [December–February 1993/94 (DJF 94)]. Extensive midlake ice formation started the second half of January, about 2 weeks earlier than normal. Seasonal maximal ice extent occurred in early February, again about 2 weeks earlier than normal. Winter 1994 maximum (normal) ice coverages on the Great Lakes are Lake Superior 96% (75%), Lake Michigan 78% (45%), Lake Huron 95% (68%), Lake Erie 97% (90%), and Lake Ontario 67% (24%). Relative to the prior 31 winters (1963–93), the extent of seasonal maximal ice cover for winter 1994 for the Great Lakes taken as a unit is exceeded by only one other winter (1979); however, other winters for individual Great Lakes had similar maximal ice covers.

Anomalously strong anticyclonic circulation over the central North Pacific (extending to the North Pole) and an abnormally strong polar vortex centered over northern Hudson Bay combined to produce a circulation pattern that brought frequent air masses of Arctic and polar origin to the eastern third of North America. New records were set for minimum temperatures on 19 January 1994 at many locations in the Great Lakes region. A winter severity index consisting of the average November–February air temperatures averaged over four sites on the perimeter of the Great Lakes (Duluth, Minnesota; Sault Ste. Marie, Michigan; Detroit, Michigan; and Buffalo, New York) indicates that winter 1994 was the 21st coldest since 1779. The unseasonably cold air temperatures produced much-above-normal ice cover over the Great Lakes and created problems for lake shipping. Numerous fatalities and injuries were attributed to the winter weather, which included several ice and snow storms. The much-below-normal air temperatures resulted in enhanced lake-effect snowfall along downwind lake shores, particularly during early to midwinter, prior to extensive ice formation in deeper lake areas. The low air temperatures were also responsible for record 1-day electrical usage and multimillion dollar costs associated with snow removal, U.S. and Canadian Coast Guard operational assistance to ships beset in ice, damage to ships by ice, damage to public and private property by river ice jams and associated flooding, frozen underground water pipes, and damage to fruit trees.

1. Introduction

Winter 1994 [December–February 1993/94 (DJF 94)] brought above-average ice coverage from the Great Lakes to the Gulf of St. Lawrence (AES 1994b). On the Hudson River, the U.S. Coast Guard (USCG) assistance to vessels beset in ice increased from 37 and 28 assists in 1993 and 1992, respectively, to more than 200 assists by mid-February 1994 (Fisher 1994a). On the Great Lakes, ice covers formed earlier and were more extensive than normal, and the popular press took note of the unusual weather and ice conditions (Associated Press 1994; Swanson 1994). Cold air outbreaks brought enhanced lake-effect snowfall along downwind lake shores of the Great Lakes before ice formed in the deeper lake areas and occasionally after that time, as ice coverage was temporarily reduced in some lake areas by episodic high winds associated with fronts and storms. Total winter precipitation (DJF 94) was below normal over most of the Great Lakes region because the jet stream over eastern North America steered many storms along the

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southern boundary of the Great Lakes or even farther southward. Frequent arctic and polar air intrusions into the midsection and eastern portion of North America, associated with the southward displacement of the jet stream over the eastern third of the continent, produced new record daily minimum air temperatures in January (NOAA 1994a). The low temperatures, in combination with the below-normal snowfall, resulted in the ground freezing to 8 ft below the surface in some regions of northern Michigan (and likely elsewhere), which in turn produced frozen and broken water lines (Fisher 1994b). The low temperatures also damaged fruit tree buds in southern Ontario (and likely elsewhere) (AES 1994a).

The ice cover that forms on the Laurentian Great Lakes each winter is an important climatic variable affecting the winter ecosystem (Vanderploeg et al. 1992), the fishery (Brown et al. 1993; Taylor et al. 1987), the economy (Niimi 1982), and lake-effect snowfall (Eichenlaub 1979, pp. 167–169). The ice cover is also an important indicator of regional climate and climate change (Assel and Robertson 1995; Hanson et al. 1992; Ryan et al. 1994; Smith 1991). In this paper, winter 1994 ice cover is placed into a climatic perspective. The synoptic meteorology of that winter is reviewed, winter temperature severity is compared with long-term records, the general seasonal and spatial progression of the 1994 ice cover is described and compared with the maximal ice cover of the previous 31 winters, and economic impacts of the anomalous ice cover and air temperatures are discussed.

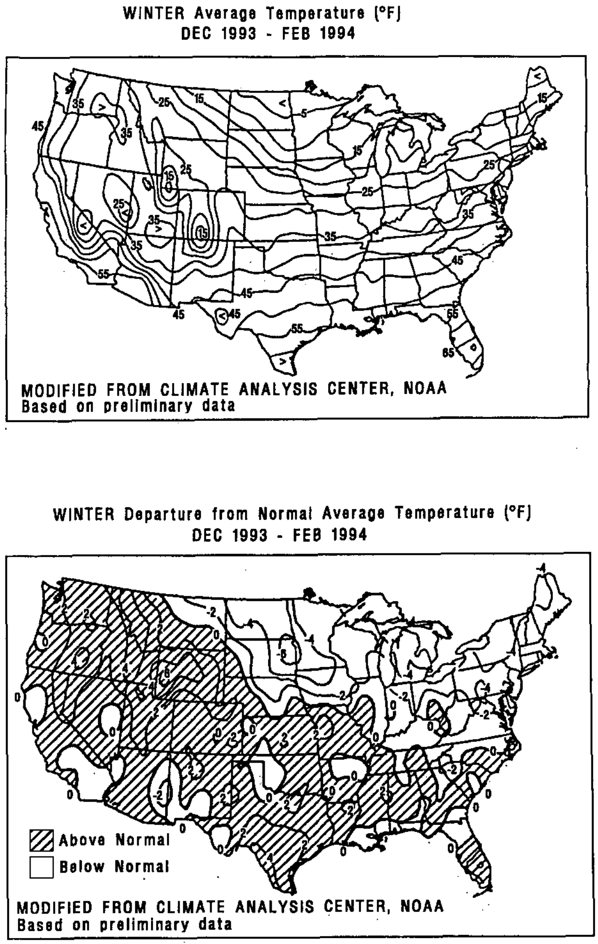

FIG. 1. (a) Temperature and (b) departure (positive values are hatched) from normal temperature for DJF 94. Units are °F.

2. Synoptic description of December–February 1993/94

a. Temperature pattern

A strong dipole in the temperature anomaly (departure from normal) pattern over the United States was observed during DJF 94 (Figs. 1 and 2). While much of the western and southern parts of the nation enjoyed a milder-than-normal winter season, unusual cold gripped the northeast and north central states, including the Great Lakes region (Figs. 1 and 2a). In much of the northeast quadrant of the United States, temperatures averaged between 4° and 6°F (2.2°–3.3°C) below normal for the entire 3-month season (Fig. 1b).

After experiencing near-normal temperatures in most of December 1993, the northeast portion of the country was subjected to an unusually cold period that began in late December, peaked in January, and continued into February (Fig. 2). Seasonal mean surface temperatures over much of the northern Great Lakes ranked among the coldest 10% on record during DJF 94, and the entire Great Lakes and surrounding region experienced temperatures that ranked in the coldest 10%–30% of the historical record. Meanwhile, the intermountain western United States experienced a relatively mild winter, especially in the northern Rocky Mountains, where mean temperatures were 4°–6°F (2.2°–3.3°C) above normal. This temperature contrast between the eastern and western parts of the country was associated with an active storm track pattern in the eastern United States that resulted in the snowiest winter on record for several locations in the northeastern United States. The mid-Atlantic and south central states were located on the southern boundary of the polar front and were subjected to numerous ice storms during the season.

b. Circulation pattern

The upper-level circulation pattern over the Northern Hemisphere during DJF 94 was characterized by below-normal geopotential heights that extended from North America, across the Atlantic and northern Europe, to far eastern Asia (Fig. 3). Meanwhile, an anomalously strong anticyclonic circulation was located over the central North Pacific and extended to the North Pole. This feature, in association with an abnormally strong polar vortex that was centered over northern Hudson Bay, was largely responsible for the entrenchment of unseasonably cold air over much of northeastern North America, as the increased meridional nature of the atmospheric flow allowed air masses of polar origin to descend on eastern North America. At the peak of the cold outbreak in the northeast and midwest United States during January, the polar vortex was considerably south of its normal position and 60–120 m deeper than normal (Fig. 4). All-time minimum temperatures were set the third week of January in the Great Lakes region. Indiana set a new state record for the lowest temperature for any date with −36°F (−37.7°C) at New Whiteland. Michigan unofficially set a new state record with a −53°F reading (−47.2°C) at Amasa, but the old record of −51°F (−46.1°C) still stands because the 1994 temperature was registered on a thermometer that was "too close to the observer's house." Marquette, Michigan, recorded its longest period ever of below-zero temperatures with 167 h (almost 7 days), while Detroit had its second longest period with 57 h.

c. Comparison with the mild 1983 winter

The monthly mean patterns of 500-mb geopotential height for winter 1983 [December 1982–February 1983, (DJF 83)] and DJF 94 depict atmospheric circulation differences between two very different winter seasons. Assel et al. (1985) indicate that for the Great Lakes region, 1983 was the 10th warmest winter since 1783 and was also the warmest winter sea-

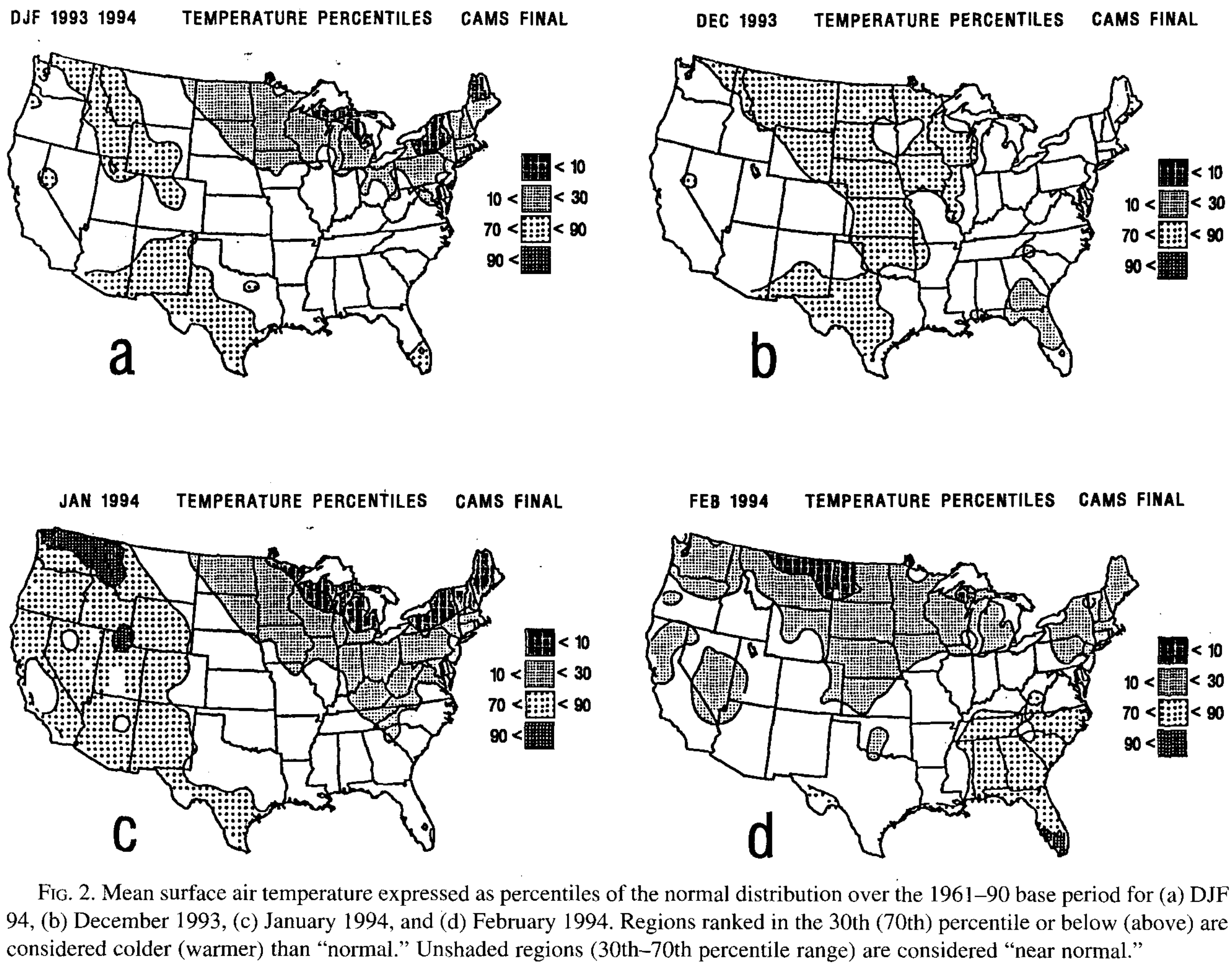

FIG. 2. Mean surface air temperature expressed as percentiles of the normal distribution over the 1961–90 base period for (a) DJF 94, (b) December 1993, (c) January 1994, and (d) February 1994. Regions ranked in the 30th (70th) percentile or below (above) are considered colder (warmer) than "normal." Unshaded regions (30th–70th percentile range) are considered "near normal."

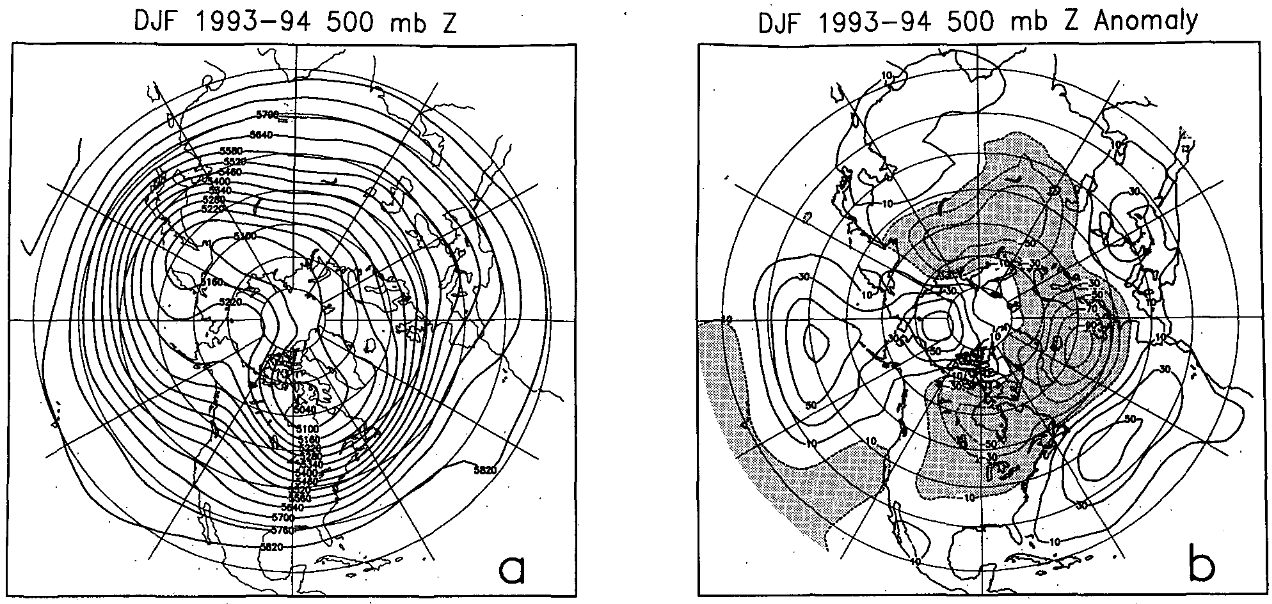

FIG. 3. The (a) 500-mb geopotential height and (b) departure from normal for DJF 94. Shaded areas indicate lower-than-normal heights. Units are m. Base period for departure from normal computations is 1979–88.

son since 1953; winter 1994, as will be seen later, was the coldest winter for the Great Lakes region since 1977 and the 21st coldest winter since 1779. The surface temperature differences for these two winters are associated with much different atmospheric circulation patterns (Figs. 5 and 6). The dominant circulation difference between the 1983 and 1994 winter seasons over North America is the abnormally strong and southerly displaced polar vortex in the Hudson Bay region that affected much of the northern United States during January and February 1994 and promoted the advection of cold polar air masses into much of central and eastern North America. While the climatological 500-mb ridge over the western United States was observed during both winter seasons, the ridge axis was farther east during DJF 83 than DJF 94, and the intensity of the ridge was considerably stronger during January and February in the former season. The differences in the circulation between DJF 83 and DJF 94 are indicated further by the striking difference

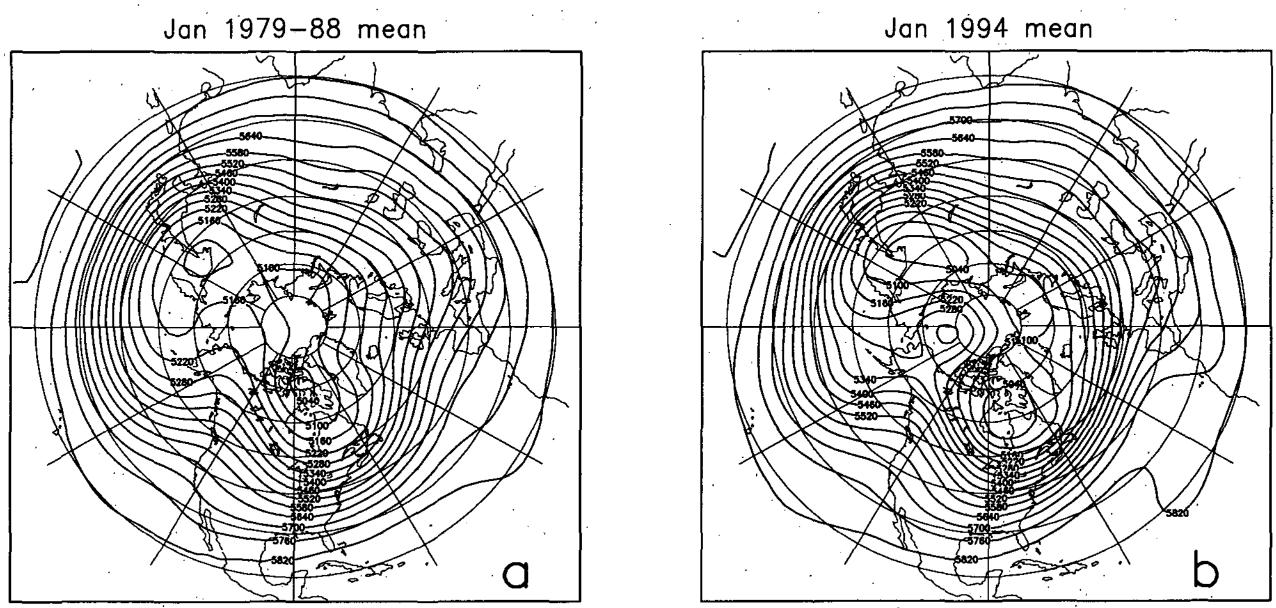

FIG. 4. January monthly mean 500-mb geopotential height for (a) 1979–88 base period and (b) 1994. Units are m.

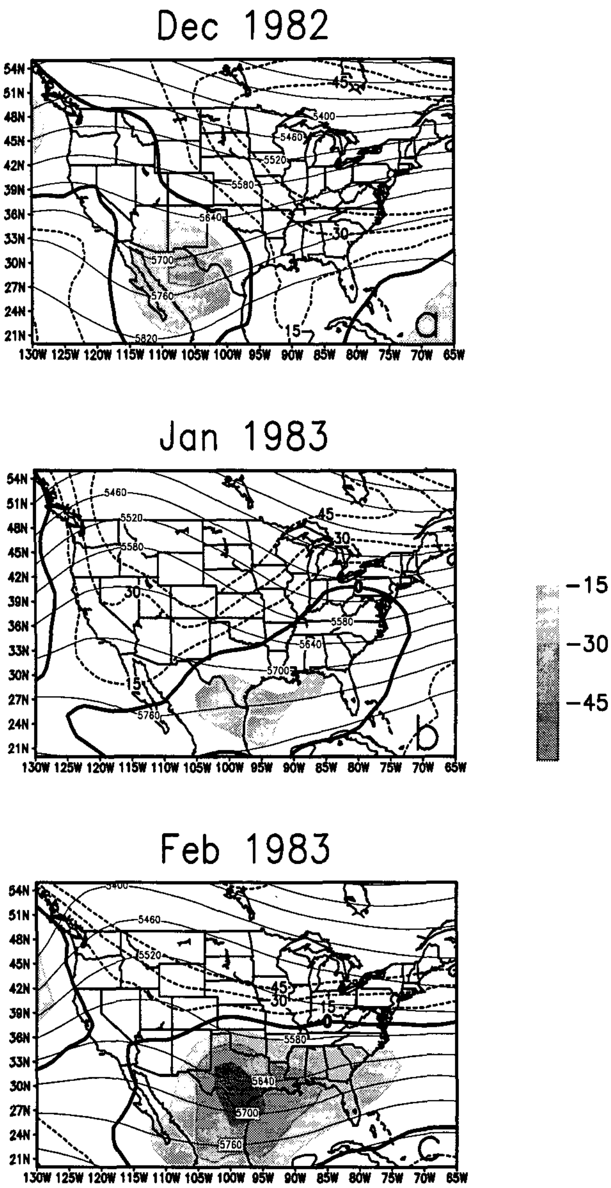

FIG. 5. The 500-mb geopotential height (solid lines) for (a) December 1982, (b) January 1983, and (c) February 1983. Positive departures from normal of 1000–500-mb thickness are denoted by dotted lines; negative departures from normal of 1000–500-mb thickness are denoted by shading. Units are m. Thick solid line denotes normal 1000–500-mb thickness.

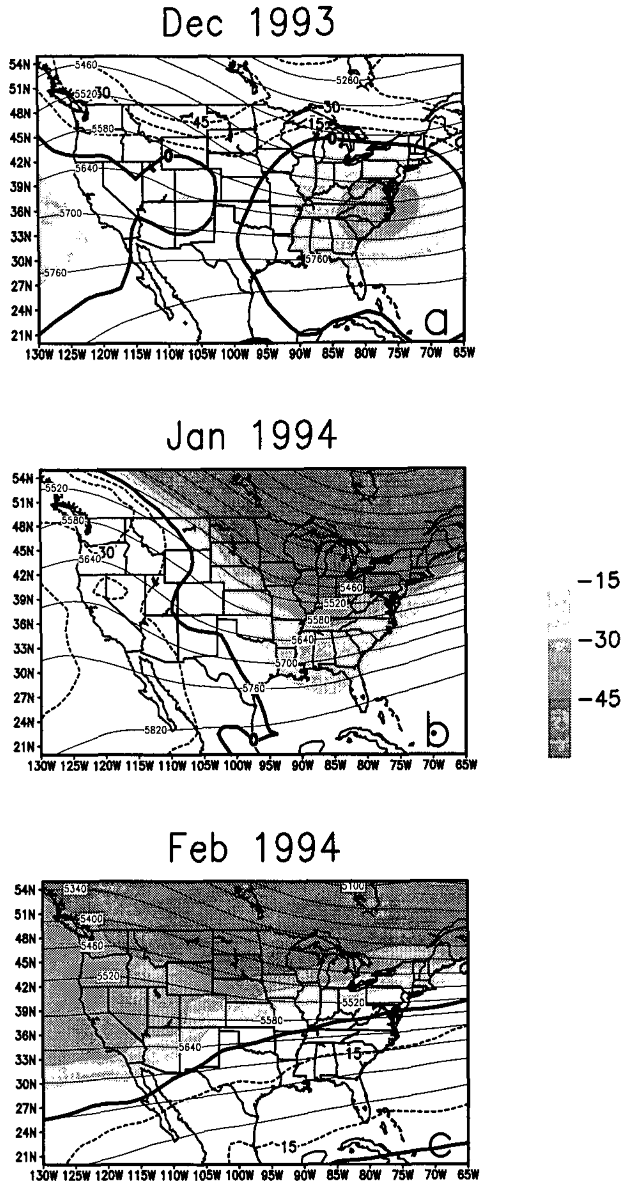

FIG. 6. As in Fig. 5 except for 1993–94.

in mean thickness between the 1000- and 500-mb geopotential height fields between the seasons (Figs. 5 and 6). The thickness between atmospheric layers (Z_1 and Z_0 at pressures P_1 and P_0) is proportional to the mean temperature in the layer by the relationship

$$T_{\text{mean}} = (Z_1 - Z_0)\left[R\ln\left(\frac{P_0}{P_1}\right)^{-1}\right], \qquad (1)$$

where R is the gas constant. Hence, thickness anomalies (departures from normal) are useful to infer atmospheric temperature anomalies within the layer. During all months of DJF 83, the 1000–500-mb thickness was much above normal over the northern half of the country and particularly in the Great Lakes region, which is consistent with the unusually warm conditions that persisted during that season. Not surprisingly, much-below-normal 1000–500-mb-thickness values occurred in DJF 94 in the northern United States, especially during January when thickness was more than 45 m below normal over most of eastern and central North America.

3. Winter severity

a. Freezing degree days

A freezing degree day (FDD) is defined as the difference between 32°F and the average of the daily maximum and daily minimum temperatures in degrees Farenheit. When the mean daily temperature on day i, T_i, is below 32°F, positive FDDs accumulate for that day; when it is above 32°F, negative FDDs accumulate for that day. Assel (1986) calculated the daily running sum of FDD accumulations, FDD(k), from 1 October to day k, where k ranged from 2 October to 30 April of the following year:

$$FDD_k = \sum_{i=\text{Oct. 1}}^{k} [32 - T_i], \qquad (2)$$

where

$$T_i = \frac{T\max_i + T\max_i}{2}.$$

If the running summation became negative on day k, as is likely to occur for days in October and November, it was set to zero, and a new sum started the following day.

Seasonal maximal FDD accumulations were calculated for 86 winters (1898–1983) for 25 sites on the perimeter of the Great Lakes and used to classify winter severity (Assel 1986). Here, that analysis was updated through winter 1994 at 12 of these sites to identify the date and amount of the winter season's maximal FDD. Winter 1994 is classified as above normal at 8 of the 12 sites (Table 1) and ranked as the 16th coldest since 1898 for the 12-site average of the annual maximum FDDs. The contemporary winters (1963–94) having higher average maximal FDD accumulations were 1963, 1970, 1977, 1978, 1979, and 1982.

The period of significant ice formation ends before or on the date of maximal FDD accumulation because that date marks the end of a period when air temperatures are generally below 32°F and the beginning of a period when air temperatures are generally above 32°F. Winter 1994 maximum FDD accumulations occurred within 4–10 days of their long-term average date at all but one site (Table 1), which is within one standard deviation of the long-term average date. Green Bay, Wisconsin, whose date of maximal FDD was 17 days earlier than average, was the exception (about 1.5 times its standard deviation).

TABLE 1. Summary of the maximum FDD: Winter 1994 FDD and 1898–1994 average. Units are °F; FDD (°F) are converted to FDD (°C) in parentheses by dividing by 1.8. Rank 1 is the highest FDD accumulation (coldest winter) during the 97-winter 1898–1994 base period. Winter severity classification based on rank: 01–19 = above normal (A), 20–77 = normal (N), 78–97 = below normal (B).

	Winter 1994		1898–1994 Average	Date of max FDD	
	Rank/Class	FDD	FDD	1994	Average
Lake Superior					
Duluth, MN	20/N	2590 (1439)	2266 (1259)	06 Apr.	01 Apr.
Marquette, MI	06/A	2257 (1254)	1523 (846)	07 Apr.	30 Mar.
Sault. Ste. Marie, MI	11/A	2281 (1267)	1807 (1004)	07 Apr.	02 Apr.
Lake Michigan					
Green Bay, WI	31/N	1535 (853)	1411 (784)	03 Mar.	20 Mar.
Milwaukee, WI	28/N	988 (549)	891 (495)	02 Mar.	10 Mar.
Chicago, IL	21/N	913 (507)	634 (352)	03 Mar.	27 Feb.
Muskegon, MI	13/A	1019 (566)	668 (371)	19 Mar.	11 Mar.
Lake Huron					
Alpena, MI	10/A	1638 (910)	1204 (669)	20 Mar.	25 Mar.
Lakes St. Clair–Erie					
Detroit, MI	16/A	832 (462)	581 (323)	02 Mar.	06 Mar.
Toledo, OH	18/A	878 (488)	571 (317)	03 Mar.	28 Feb.
Cleveland, OH	19/A	704 (391)	452 (251)	14 Feb.	24 Feb.
Buffalo, NY	18/A	902 (501)	644 (358)	21 Mar.	11 Mar.

This much-earlier maximum FDD accumulation is attributed to a warming trend on 3–7 March, when daily temperatures ranged from 40° to 53°F (4.4° to 11.7°C) at Green Bay.

The influence of site position and latitude relative to the lake ice cover is apparent in the geographic distribution of the dates of maximal FDD accumulation in winter 1994. The latest dates, in early April, occurred on Lake Superior (the most northerly of the Great Lakes, with the greatest area of ice in spring 1994). The earliest dates (mid-February to early March) occurred on the western shore of Lake Michigan and the southwestern shores of lakes St. Clair and Erie (stations at the most southerly latitudes and/or upwind of ice-covered lake areas). Maximal FDD dates occurred in the last half of March on southeastern Lake Michigan, northern Lake Huron, eastern Lake Erie, and southern Lake Ontario (sites downwind of large areas of ice cover and/or north of 45°N).

b. Regional monthly air temperature

A winter severity index consisting of the average November–February air temperatures averaged over four sites on the perimeter of the Great Lakes (Duluth, Sault Ste. Marie, Detroit, and Buffalo) was developed by Snider in Quinn et al. (1978) and used to identify the 20 coldest winters in the past 200 years. DeWitt et al. (1980) updated that index through 1979 and identified the 22 coldest winters over the past 200 years, and Assel et al. (1985) updated that index to identify the 20 mildest winters over the past 200 years. The index for winter 1994 is one of the highest (coldest winters) during the past 215 years (Table 2), and only 9% of the winters from 1780 to 1994 were ranked higher than 1994. Assel et al. (1985) calculated an annual maximal regional ice cover, defined as the percentage of total surface area covered by ice of all five Great Lakes at the time of maximal ice extent on each lake, and developed a regression between regional ice cover and the winter severity index. Here, that regression (Fig. 7) was updated through winter 1994. The observed regional ice cover for winter 1994 was 89%; the projected regional ice cover for the 20 winters colder than 1994 (Table 2)

TABLE 2. The 21 coldest winters since 1779. Table modified from Table 5 in DeWitt et al. (1980). Each of the coldest winters was characterized as early (E), intermediate (I), or late (L) according to the timing of its coldest period.

Rank	Winter	Nov.–Feb. Mean (°C)	Nov.–Feb. Temp. (°F)	Nov.–Jan. Mean (°C)	Nov.–Jan. Temp. (°F)	Character
1	1780	−9.0	15.8	−10.0	14.0	E
2	1875	−9.0	15.8	−6.5*	20.3	L
3	1784	−8.0	17.6	−6.5*	20.3	L
4	1904	−7.9	17.8	−6.2	20.8	L
5	1977	−7.7	18.1	−8.2	17.2	E
6	1873	−7.5*	18.5	−7.5*	18.5	I
7	1832	−7.5*	18.5	−6.5*	20.3	L
8	1856	−7.5*	18.5	−6.0	21.2	L
9	1920	−7.4	18.7	−7.0	19.4	L
10	1881	−7.3	18.9	−7.2	19.0	I
11	1918	−7.2	19.0	−6.8	19.8	L
12	1821	−7.0	19.4	−7.0	19.4	I
13	1857	−7.0	19.4	−7.0	19.4	I
14	1823	−7.0	19.4	−4.5*	23.9	L
15	1893	−6.8	19.8	−5.8	21.6	L
16	1979	−6.8	19.8	−5.1	22.8	L
17	1963	−6.5	20.3	−6.3	20.7	L
18	1792	−6.5*	20.3	−6.0	21.2	L
19	1836	−6.5*	20.3	−5.5*	22.1	L
20	1818	−6.5*	20.3	−5.0	23.0	L
21	1994	−6.4	20.5	−5.4	22.2	L

*Data prior to 1888 were not of sufficient quality to justify means with 0.1°C precision. They have been rounded off to the nearest 0.5°C.

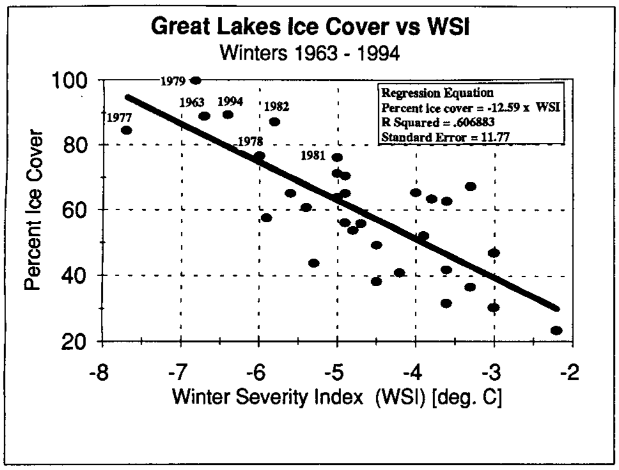

FIG. 7. Winter severity index vs regional Great Lakes ice cover: winters 1963–94.

ranged from 82% to 100%, lending credence to the severity of the ice cover for this remarkable winter.

4. Normal seasonal ice cover progression and the 1994 Great Lakes ice cycle

a. Data

Spatial distribution patterns of ice conditions for a given date are summarized graphically for the Great Lakes on composite ice charts, compiled from aerial ice reconnaissance (visual and radar observations), ship reports, shore reports, and satellite imagery by the U.S. National Ice Center (NIC) and the Canadian Atmospheric Environment Service (AES). Composite ice charts often contain observations that preceded the date of the ice chart by several days because a synoptic observation of ice conditions over the entire surface area of the Great Lakes during winter is not usually possible due to clouds and bad weather. To provide an estimate of synoptic ice conditions, observations preceding the date on the composite ice chart are occasionally modified to take into account weather conditions between the date of observation and the date of the ice chart. In winter 1994, composite ice charts were produced three times per week by the NIC and weekly by the AES, starting in December and continuing into early May. Several of these ice charts are presented here (in a modified format) to portray ice formation before and after the cold wave of 15–19 January (Figs. 8a and 8b), the period when the lakes were near their seasonal maximal ice cover extent (Figs. 8c and 8d), and the spring ice loss period (Fig. 8e). Ice charts were also analyzed to estimate the percentage of lake surface area covered by ice during the period of seasonal maximum ice cover for winter 1994.

b. Contemporary seasonal and spatial progression of Great Lakes ice cover

Ice cover forms in shallow bays and harbors of the Great Lakes in December and in the larger and deeper bays and in the shallow areas of the entire Great Lakes (including all of Lake Erie) in January. During February and the first half of March, ice forms over the deeper, more exposed areas of the Great Lakes and reaches its maximal areal extent. Even at the time of maximal extent, the Great Lakes (with the exception of Lake Erie) do not usually approach 100% ice cover (Table 3). This is because winds break up and move existing ice (Richards 1964; Rondy 1976) and cause upwelling of relatively warmer waters in deep lake areas to melt ice covers or prevent them from forming. The low maximal ice cover on Lakes Michigan and Ontario (Table 3) is due to the combination of moderate winter air temperatures and large mean depth (and associated large heat storage capacity). Lake Erie, which is also exposed to mild winter air temperatures, forms a much more extensive ice cover because of its much smaller mean depth. During a

TABLE 3. Summary of Great Lakes physical features, seasonal maximal FDD, and ice cover.

	Superior	Michigan	Huron	Erie	Ontario
Mean depth (m)	148	85	59	19	86
Surface area (km^2)*	82	58	59	26	19
Normal max FDD (°C)+	928	447	572	216	324
Normal max FDD (°F)	1670	804	1030	389	583
Normal max ice (%)#	75	45	68	90	24
1994 max ice (%)	96	89	95	97	67

*Rounded to nearest 1000 km^2.
+From Assel (1986).
#From Assel et al. (1983).

mild year, such as 1983, ice cover is confined to shallow areas of the Great Lakes (Assel et al. 1985). During a severe winter, such as 1979, ice cover can exceed 90% on all the Great Lakes (DeWitt et al. 1980). Ice cover is usually lost over the midlake areas in March and April. The Great Lakes are virtually ice free by the end of April for most winters with the exception of limited amounts of windblown ice and shore ice.

Over the past 31 winters prior to 1994, only 1979 had greater observed regional maximal ice cover (Fig. 7). Other contemporary winters with regional maximal ice cover in excess of 80% were 1982, 1977, and 1963. Below (sections 4c–4g), an overview of the normal seasonal progression of ice cover for each Great Lake (summarized from Assel et al. 1983) precedes an overview of the spatial and seasonal pattern of ice formation and loss for 1994. Unless stated otherwise, reference to above- or below-normal ice cover is with respect to the normal ice charts given in Assel et al. (1983), and percent ice cover refers to the percentage of the total surface area of the lake covered by ice. Most place names in the proceeding discussion are given in Fig. 9.

c. *Lake Superior*

1) Normal ice cover

Lake Superior has the largest surface area and the greatest mean depth (volume divided by surface area) of the five Great Lakes (Table 3). It is also exposed to the lowest air temperatures by virtue of its most northerly and westerly location. Ice can form in shallows in late November or early December, but due to this lake's great depth, ice cover is usually confined to bays, harbors, and coastal areas through the end of January. During the first half of February, ice covers all of the western basin from Duluth to the Keweenaw Peninsula, excluding the central area south of Isle Royale, and ice forms along the perimeter of the eastern basin extending 20–40 km away from the shores from Keweenaw Peninsula to Michipicoten. The normal maximum ice cover, 75%, occurs during the second half of February. Ice formation can continue through the end of March, although loss of ice cover due to moderating weather also usually starts in March. During the last half of April, the remaining ice is confined to bays, harbors, and havens for wind-driven ice. This lake usually is ice free by early to mid-May.

2) Winter 1994 ice cover

On 3 December the first ice for the 1994 winter was observed in the northern coastal areas of Thunder, Black, and Nipigon Bays and in Duluth Harbor. Low air temperatures during the last 10 days of December produced ice cover from Duluth Harbor to beyond the Apostle Islands along the shoal area of the southwest shore of Lake Superior. Ice cover was above normal by the second half of January, first west of the Keweenaw Peninsula (Fig. 8b), then over the entire lake by the end of the month. The lake was within 10% of its seasonal maximum ice cover of 96% from 7 February to the end of the month (Figs. 8c and 8d).

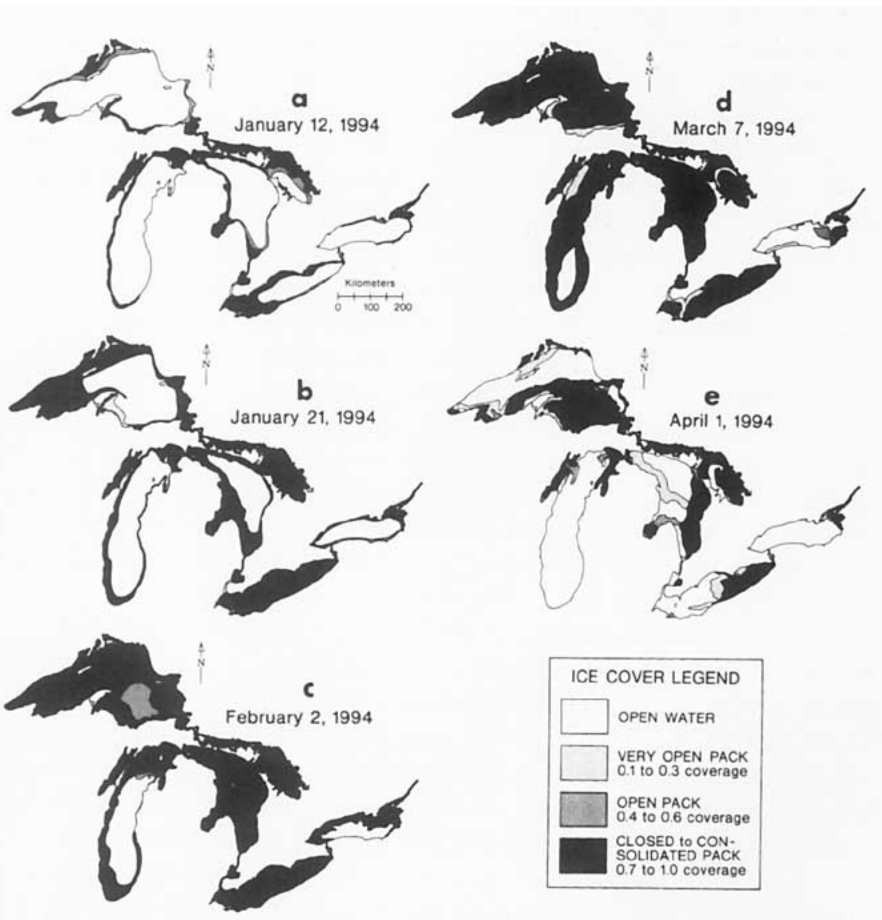

Fig. 8. Winter 1994 ice distribution patterns abstracted from National Ice Center composite ice charts for (a) 12 January, (b) 21 January, (c) 2 February, (d) 7 March, and (e) 1 April.

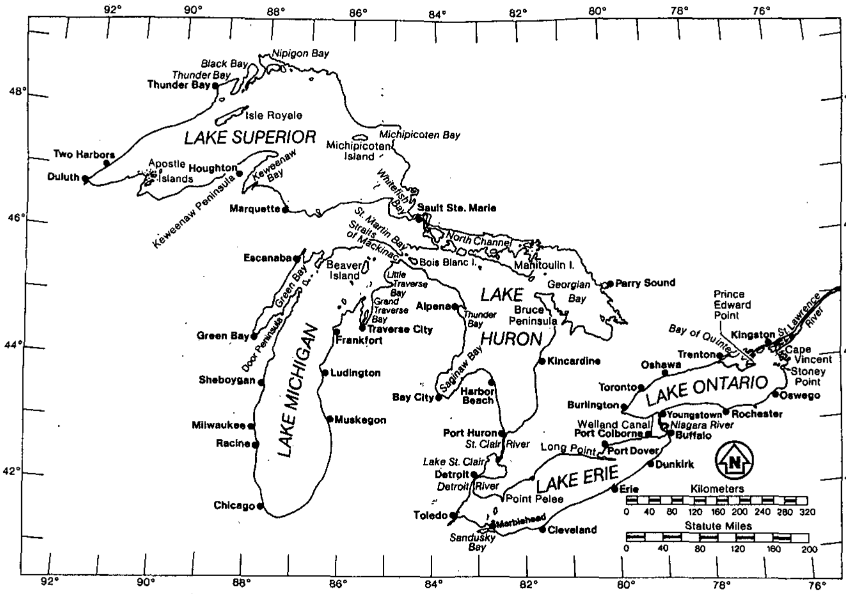

FIG. 9. Map of place names.

The normal ice covers for the first and second halves of February are 38% and 75%, respectively. The maximal ice cover during winter 1994 was most similar in timing, duration, and extent to winter 1979 (99%+), although other winters with estimated maximal ice cover of 90% or more include 1963 (95%), 1965 (90%), 1968 (90%), 1972 (95%), 1981 (92%), and 1989 (91%). During the first week of March, above-normal temperatures and winds caused cracks along the fast ice edge of the northwestern shore from Grand Portage Bay (northwest of Isle Royale) to Two Harbors. Winds, over several days, expanded the cracks into small open water areas. This marked the onset of the ice decay period (break up and melting of the ice cover). However, the ice decay period was prolonged due to a greater-than-normal ice mass that formed earlier in the winter and due to the greater-than-normal rafting and ridging of windblown ice in March. By the end of March, the lake still had above-normal ice cover and was 90%–100% ice covered south of a line from Michipicoten to the Apostle Islands (Fig. 8e). Air temperatures for the first half of April were 2.6°F (1.4°C) below normal, and much of the ice cover remained intact with some reductions in concentrations. Near-normal air temperatures and southwest winds during the second half of April reduced the ice cover and drove the remaining ice into the eastern lake shore from Michipicoten Island southward. This ice loss was mostly by in situ melting, which continued until mid-May. Lake Superior was virtually ice free on 17 May.

d. Lake Michigan

1) Normal ice cover

Lake Michigan has the third largest surface area and the third greatest mean depth of the Great Lakes. Large synoptic differences in atmospheric and ice conditions occur on Lake Michigan due to its long north–south axis that spans 4 degrees of latitude. Ice formation on this lake begins in the coastal areas of the northeastern basin and Green Bay during the second half of December. Coastal ice formation migrates southward the first half of January. Ice formation begins to occur in midlake regions during the second half of January and the first half of February. The normal maximum extent of ice cover, 45%, is attained by the second half of February. A large decrease in midlake ice cover occurs during the first half of March, marking the beginning of the ice decay period; however, due to the large north-to-south temperature gradient, ice formation continues in the northern portion of midlake areas until the end of March. The ice edge retreats northward as the month progresses, leaving higher ice concentrations in Green Bay and in the lake region between Beaver Island and the Straits of Mackinac. Ice lingers on this lake until the end of April.

2) Winter 1994 ice cover

Ice was first observed in northern Green Bay on 10 December during winter 1994. By the end of December, the mouth of the bay was 95%–100% covered with thin ice (5–15 cm), and the rest of the bay was 100% ice covered; the Straits of Mackinac also had shorefast ice, and most of the lake's perimeter contained a limited amount of coastal ice extending a few kilometers into the lake. During the first half of January, the ice edge expanded from the Straits of Mackinac to Beaver Island and out from shore elsewhere along the lake's perimeter approximately 5–15 km (Fig. 8a). Ice cover continued to increase in extent in midlake (although in a somewhat irregular fashion) over the next four weeks (Figs. 8b and 8c). By mid-February, the lake was estimated to be 89% ice covered and near its seasonal maximal ice cover. Because of its long north-to-south extent, it is only during winters when much-below-normal air temperatures persist in the southern half of the lake that ice cover in excess of 50% develops on this lake (Assel and Quinn 1979). Winters with seasonal maximal ice covers in excess of 80% during the past 32 years included 1963 (80%), 1977 (90%), and 1979 (99%+). Winter 1994 ice cover consisted of mostly thick ice (30–70 cm) with lower concentrations of thin (5–15 cm) and new ice (0–5 cm) located in the central region of the lake. Air temperatures first increased sharply during the third week of February (reducing the midlake ice cover) and then returned to below-normal values the final week of February and into early March. The lake was again near its seasonal maximal ice cover on 2 March (Fig. 8d). However, above-normal temperatures later that same week [58°F (14.4°C) at Chicago, 53°F (11.7°C) at Milwaukee, and similar temperatures at surrounding weather stations] caused large and rapid reductions of the midlake areas of thin ice cover. By 15 March, the midlake region of the lake south of Green Bay was virtually ice free. Ice breakup in Green Bay started the second half of March in the southern end of the bay. At the onset of April, a lead could be seen from Escanaba to the open water area at the mouth of Green Bay (Fig. 8e). Small leads also surrounded the southern perimeter of southern Green Bay. The northeast area of the lake and the Straits of Mackinac remained consolidated with very thick ice (>70 cm). Air temperatures 16°F (8.9°C) above normal during the third week of April further reduced the ice cover on Green Bay. By 18 April, most of Green Bay was ice free, and the ice in the main lake had receded north of Beaver Island. Prevailing westerlies compacted the remaining ice into the coastal areas entering the Straits of Mackinac. The lake was estimated to be virtually ice free by 26 April.

e. Lake Huron

1) Normal ice cover

Lake Huron has the second largest surface area and the fourth largest mean depth. Ice formation begins in the shallow embayments of the Straits of Mackinac, the North Channel, Georgian Bay, and Saginaw Bay in December. In January, North Channel, the northeast shore of Georgian Bay, and Saginaw Bay become 70%–100% ice covered, and ice of various concentrations lines much of the rest of the lake's perimeter. The normal maximum ice extent, 68%, occurs by the second half of February, at which time only the deepest portion of the lake—the midlake area between Alpena to the west and Kincardine and the Bruce Peninsula to the east—remains relatively ice free. Ice cover is lost gradually during March, first in the midlake areas and more slowly in the bays and constricted shore areas. During April, the bulk of the remaining ice is located in North Channel, Saginaw Bay, and Georgian Bay. The lake is usually ice free by late April or early May.

2) Winter 1994 ice cover

In winter 1994, ice was first observed along the coastal areas of North Channel and Georgian Bay on 24 December. Air temperatures at Alpena during the last week of December averaged −15.5°F (−26.4°C). Similar temperatures were recorded at other stations surrounding this lake. Ice cover was above normal by the end of December: North Channel and Saginaw Bay were 90%–100% ice covered, coastal ice lined the entire northeastern shore of Georgian Bay and the western shores from Alpena to Port Huron, and the Straits of Mackinac had extensive shorefast ice. Georgian Bay normally reaches 90% ice cover by the first half of February; it was 100% ice covered around mid-January. During the second half of January, below-normal air temperature caused much-above-normal ice cover to form in midlake areas (Fig. 8b). By the end of January, the only large open water area was located in the center of the lake, and Lake Huron's ice cover substantially exceeded the normal maximal ice cover. By 7 February (Fig. 8c), the lake was estimated to be 95% ice covered (the seasonal maximum ice extent), a value that exceeded the normal maximum ice cover (68%) by 27%; the maximal ice cover was also two weeks earlier than normal. Seasons with similar maximal ice cover extent over the prior 31 winters included the winters of 1963 (97%), 1977 (90%), 1978 (89%), 1979 (100%), 1981 (89%), and 1982 (100%). The lake is estimated to have maintained an 85%–95% ice cover through 7 March (Fig. 8d); for the next several days, prevailing southwesterly winds created a lead along the western shore areas from Cheboygan (south of Bois Blanc Island) to Port Huron, excluding Saginaw Bay. A few days later, cracks developed along the southern coast of Manitoulin Island and along the fast ice in Georgian Bay. The midlake ice cover and the ice cover in Georgian Bay gradually receded toward the east and south from the beginning of the second week of March through the end of the third week in April, when the midlake was for all practical purposes ice free, and the ice cover in Georgian Bay was located primarily along the eastern shore (Fig. 8e). Ice cover loss on Saginaw Bay began the last week of March, and most of the ice was gone by 9 April. Dissipation of ice in the North Channel began near the end of the third week of April, and the entire lake was virtually ice free by 5 May.

f. Lake Erie

1) Normal ice cover

Lake Erie has the fourth largest surface area and is the shallowest and farthest south of the Great Lakes. Its small mean depth (Table 3), in comparison to the other lakes, accounts for its extensive ice formation, despite its relatively mild winter temperatures. This lake consists of three basins: a shallow west basin from the west end of the lake to Point Pelee, a central basin from Point Pelee to Long Point, and an eastern basin from Long Point east to the head of the Niagara River. Ice usually forms in the shallows along the entire lake perimeter and in the western lake basin in December. The west lake basin is usually 70%–90% ice covered by mid-January, and ice of lower concentrations occurs over the central and eastern basins. The normal seasonal maximal ice cover of 90% occurs in February; this is the only Great Lake where the normal seasonal maximum extent lasts an entire month. During the first half of March, ice concentrations are reduced in the western lake basin and along the shores of the central basin. During the second half of March, the ice concentrations are reduced in the central basin and eastern lake basins. By mid-April, the west basin and most of the central lake basin are ice free. The only large area of ice in the lake during the second half of April is located in the eastern end of the east basin. Wind-induced rafted ice occasionally persists in the northeastern end of the lake throughout early to mid May.

2) Winter 1994 ice cover

Shore ice was reported in winter 1994 during the last week of December (at Erie and Cleveland). The entire western lake basin was estimated to be 90% ice covered by the end of December, about two weeks earlier than normal. The International Niagara Working Committee (1994) reported that ice also began forming at the east end of Lake Erie near the end of December, earlier than normal. The entire lake was estimated to be in excess of 90% ice covered near mid-January, about two–three weeks earlier than normal. The lake was at its seasonal maximum ice cover, 97%, on 7 February (Fig. 8c). Lake Erie remained in excess of 90% ice covered through approximately the third week of February, when open-water areas formed along the shore in the central basin and in the island area between the west and central basin. Prevailing winds associated with brief warming trends increased the open-water areas and created rafting and ridging of the ice cover during the final week of February. Low temperatures near the end of the month and in early March brought new ice formation, and the lake was once more 80%–90% ice covered (Fig. 8d). Ice covers were above normal for most of March. The west lake basin and the west half of the central lake basin were virtually ice free by the end of March (Fig. 8e); the remainder of the central lake basin was predominately ice free by mid-April. Removal of the Niagara River ice boom at the east end of Lake Erie was delayed until 21 April, 13 days past its average opening date of 8 April, because of the large amount of ice in eastern Lake Erie (International Niagara Working Committee 1994). Ice was confined to the eastern end of the lake, east of Port Colborne, by 25 April. The date of last reported ice, 1 May, was 7 days later than the 90-year (1905–94) average date of 24 April.

g. Lake Ontario

1) Normal ice cover

Lake Ontario has the second largest mean depth and the smallest surface area of the Great Lakes. This lake is exposed to milder winter air temperatures compared to Lakes Superior, Michigan, and Huron (Table 3) because of its southeastern location relative to the other Great Lakes. As a result of its large heat storage and relatively mild winter temperatures, the midlake area of Lake Ontario usually remains open water, with the possible exception of infrequent episodic cold calm periods when thin ice cover may form for several days and then be lost due to wind-induced breakup and melt. Ice formation starts in shallow shore areas, such as the Bay of Quinte, and in embayments along the northeastern shore in December. By the last half of January, coastal ice lines the lake in an arc from Prince Edward Island to Stoney Point and in other shallow shore areas. The lake attains its normal seasonal maximum ice extent of 24% during the second half of February. Ice starts to recede during the first half of March along the southern shore and western perimeter of the lake. During the second half of March, ice gradually recedes in the northeastern lake from Stoney Point to Prince Edward Island. The lake is ice free by the second half of April.

2) WINTER 1994 ICE COVER

Ice was reported in the Bay of Quinte 2 days after Christmas in winter 1994. By the end of the first week of January, ice cover extended from the southwestern end of Prince Edward Island eastward to Stoney Point and lined the perimeter of the southern coast over to the Niagara River. The ice formation between Prince Edward Island and Stoney Point was above normal for the first half of January (Fig. 8a); air temperature averaged 7.5°F (4.2°C) below normal for the first half of January. By mid-January, the ice covered over 24% of the lake surface, the normal seasonal maximum that usually occurs during the second half of February. During the second half of January, air temperatures increased and were accompanied by predominantly southwesterly winds. These conditions resulted in the melting of the newly formed ice as the winds pushed the ice along the southern coast into warmer midlake waters. During the last 2 days of January, air temperatures fell sharply, causing ice formation along the northern coast of the lake. Below-normal air temperatures continued into February (Fig. 8c). By mid-February, the midlake area in an arc from Rochester north to Trenton then east to Toronto was ice covered with various ice concentrations; the lake was estimated to be 67% ice covered. This was Lake Ontario's maximum ice cover for winter 1994. Only four other winters over the prior 31 winters had maximal ice cover that exceeded 50%: 1963 (51%), 1978 (57%), 1979 (95%), and 1982 (53%). For the next 7 days a warming trend [extreme air temperatures up to 30°F (16.7°C) above normal] accompanied by southerly winds resulted in loss of virtually all of the midlake ice cover. More seasonable air temperatures during the last few days of February brought short-lived new midlake ice formation in approximately the eastern third of the lake, some of which remained through early March (Fig. 8d). That midlake ice was lost over the first half of March. By the end of the month, the main body of ice cover left in the lake was located north of an arc from Prince Edward Island to Stoney Point. This ice was lost gradually over the next three weeks; the lake was ice free by 25 April.

5. Economic impact of the 1994 winter

The winter weather of 1994 had tremendous economic and personal impact on the people of the Great Lakes region. Effects of winter weather related to personal injury, snow removal costs, property damage, and shipping are discussed below and summarized in Table 4.

a. Personal injuries

The first fatalities of the winter were reported in late December: an 86-year-old woman fell in Westfield, Indiana, and died from exposure to the cold on 26 December; a homeless man died of hypothermia on 28 December in Toledo, Ohio. On 4 January, 185 people were injured in western Pennsylvania; 10 died of heart attacks while shoveling heavy snow that blanketed the region (NOAA 1994b). Fatalities due to exposure to the extreme cold during the third week of January were numerous. Three died in Pennsylvania, 10 in Ohio, 3 in Indiana, and 1 in Wisconsin. Ice storms on 8 and 11 February resulted in 1 fatality (due to exposure) and 1594 injuries due to falls and other accidents. A building collapsed from heavy snow at Stoney Creek, New York, on 12 March, killing one person. Thus, numerous reported fatalities and injuries were related to the winter weather (primarily the bitter cold).

b. Snow removal costs and property damage

The below-normal temperatures during late December 1993 and much of January 1994 resulted in millions of dollars in snow removal costs. During the second week of January, 3 ft (0.9 m) of snow fell on the Keweenaw Peninsula area of the Upper Peninsula of Michigan and up to 1 ft (0.3 m) was reported across much of the Lower Peninsula. Strong east winds with gusts up to 35 mi h^{-1} (15.4 m s^{-1}) caused considerable blowing and drifting of the snow; drifts of 3–5 ft (0.9–1.5 m) were common, and Michigan sources (NOAA 1994b) estimated that over a million dollars was spent on snow removal for this single storm.

Damages to both private and public property also amounted to millions of dollars because of the bitter cold. Frozen pipes were all too common throughout the region, especially during the third week of January. Many towns in Michigan's Upper Peninsula reported their entire water systems were frozen for nearly a week. The severe cold of the third week of January brought lake-effect snowfall, collapsing six buildings in northeast Ohio and record 1-day electricity demand at Detroit Edison. A warm spell during the last week of January produced ice-jam flooding on rivers in Pennsylvania and Ohio. One to two inches (2.5–5 cm) of rain fell on top of melting snow and saturated the ground, producing ice runs down rivers that resulted in injury to people and property damage totaling several million dollars (Table 4). Ice storms

TABLE 4. A chronology of Great Lakes weather events and their related impacts—winter 1994.

21–31 December 1993: Cold spell and lake-effect snow
- Two fatalities (Westfield, IN; Toledo, OH) due to exposure and hypothermia.
- Water main breaks; fires due to residents use of additional heat sources.
- Ship beset in ice at Saginaw Bay, Lake Huron.
- Snowfall: 24 in. (61 cm) Lakes Superior and Erie snowbelts; 12–18 in. (30.5–45.7 cm) Lake Ontario snowbelt.

1–7 January 1994: Continued cold and snow storm
- Coast Guard assists ships beset in the ice on the St. Marys River the Straits of Mackinac, Saginaw Bay, and in the St. Clair River.
- Detroit Edison sets new 1-day all-time power generation record (6 Jan.).

8–14 January 1994: Continued cold and snow storm
- Snowfalls, 35 mi h^{-1} winds (15.4 m s^{-1}), 3–5 ft (0.9–1.5 m) snow drifts in Michigan; over $1,000,000 for snow removal.
- Nine U.S. Coast Guard and two Canadian Coast Guard vessels answered requests for assistance and track maintenance in Saginaw Bay, Toledo harbor, western Lake Erie, and Cleveland harbor.

15–21 January 1994: Record breaking cold on 19 Jan.
- Fatalities due to exposure were numerous: 3 in PA, 10 in OH, 3 in IN, and 1 in WI.
- Ice on the Great Lakes was severe; ice breaking operations were underway on four of the five Great Lakes simultaneously; Lake Ontario, the fifth lake, might have been included if the St. Lawrence Seaway and Welland Canal had not closed in late December. The U.S. and Canadian Coast Guards assisted ships in the Straits of Mackinac, northern Green Bay, southern Lake Huron, and in Lake Erie. The binational icebreaking forces reported that their icebreaking operational hours and vessel assistance figures through mid-January were higher than the three previous winters combined at that point in the winter. The Ohio River, another key navigation waterway, had significant ice cover, and barge traffic was slowed as a result.
- Detroit Edison set another daily power usage record on 18 January. Other areas were without power because the extreme cold caused power lines to contract and snap off from their poles.
- The cold wave brought 2–4 ft (0.6–1.2 m) of snow to all counties downwind and adjacent to Lake Michigan. Snow in Ohio collapsed six buildings in the northeast counties, and two teenagers were killed in separate incidents.

22–31 January 1994: Milder temperatures, rain, melting, ice jams, and ice storms
- One to 2 in. (5 cm) of rain and melting snow brought ice jam–related flooding in PA and OH. The Coast Guard assisted in breaking up the ice jams near the mouth of the Grand River at Fairport Harbor, OH, but the shallow shoreline areas in other harbors prevented Coast Guard vessels from reaching the critical jams upriver. The ice jam on the Chagrin River east of Cleveland, OH, cut loose on 28–29 January destroying 1 home and damaging 65 others. Six people were injured, and property damage totaled several millions of dollars.

the last week of January resulted in utility power outages in northwest Illinois. Ice storms in the first half of February (on 8 and 11) in Ohio resulted in millions of dollars in damages to buildings. Mild weather and snow storms during the last half of February brought ice-jam flooding in many Great Lakes areas, again causing property damage in the millions of dollars and stranding motorists on the highways. In March, ice-jam floods occurred again in Michigan ($260,000 in damage), and heavy snows were reported in New York, Pennsylvania, and upper Michigan.

c. Shipping

U. S. Coast Guard vessels assigned to the Ninth Coast Guard District (Cleveland, Ohio), which serves all of the Great Lakes, logged over 5700 h (2376 h in directly assisting beset commercial vessels and escorting other vessels through heavy ice fields, over 3200 h grooming vessel tracks, and over 177 h in flood relief operations in rivers) to keep shipping underway during winter 1994. Coast Guard aircraft logged over 500 h in winter 1994. This is the greatest number of U.S. Coast Guard ship and aircraft hours logged for winter operations over at least the past 15 winters (Table 5). Countless hours were expended by the Canadian Coast Guard as well. As a result of the massive effort by the shipping industry and the binational Coast Guard forces, well over $130 million of cargo reached its destination safely (U.S. Coast Guard 1994). Many of the vessels carried petroleum products or coal that was vitally needed by power companies and factories to generate electricity or heat. The heavy ice conditions on the Great Lakes in March and early April resulted in delays of 1–16 days (Table 6)

Table 4. (*Continued*)

1–14 February 1994: Ice storms, ice jams, and lake-effect snowfall
- Up to 1 ft (0.3 m) of lake-effect snow fell on northeastern Ohio on 3 February.
- U.S. Coast Guard assisted in ice-jam flood relief operations in Fairport Harbor and Vermilion, OH.
- High winds on Lake Erie from a storm on 11 February caused a tug to heel 65° in the ice. The Canadian Coast Guard assisted the tug to Rondeau, Ontario, where it later sank at the dock due to the previous ice damage.

15–28 February 1994: Continued mild, ice jams, and a snow storm on 22 February
- Ice-jam flooding became a problem in many Great Lakes areas due to the mild weather: the Raisin River (Monroe, MI; several million dollars damage), the Fox River in WI, and along the Lake Erie shoreline in OH and NY. Forty people were evacuated in Kenosha County, WI. Two fatalities were reported in Darlington, WI.
- A snowstorm (22–25 February) left 1400 motorists stranded in Elkhart, IN, and caused a 25-car pileup on I-96 in southern MI.
- The thawing and high winds combined to produce even worse conditions on the Great Lakes. Ice cover was loosened by the milder weather, and then the winds caused considerable rafting and ridging of the ice cover—comparable to snow drifts on land. Anticipating a formidable spring breakout, the U.S. and Canadian Coast Guards developed a Joint Contingency Plan, each country requested an additional icebreaker from outside the Great Lakes region to assist through the spring.

1 March–24 April 1994: Ice jams, ice storms, high winds, and a new navigation season
- An ice jam caused flooding on the Grand River in Ottawa County, MI; 41 people were evacuated, damage to docks was $260,000.
- Heavy lake-effect snows (2–3 and 9–10 March) resulted in 12 fatalities in Stoney Creek, NY, when a building collapsed; an ice storm in Ohio (9–10 March) caused 14 injuries.
- Gale force winds on 14 March put the ice cover on the northern waters of the Great Lakes under considerable pressure (rafting and ridging). Ice also continued to grow and refreeze. The SS *Kaye E. Barker* was beset in the ice east of Erie, PA, on 16 March. It took U.S. and Canadian Coast Guard vessels 5 days to free her. The USCG icebreaker *Mackinaw* broke out Whitefish Bay (Lake Superior) but she left no discernable track due to the thickness and extremely heavy ridging and rafting. The Coast Guard assisted three vessels into northern Green Bay, where high winds closed the previously established track to Escanabe. The *Mackinaw* escorted convoys across Lake Superior through mid-April. The last direct assistance by a Coast Guard vessel was made by the *Mackinaw* in eastern Lake Huron on 24 April.

in scheduled departure dates for ships of the Lake Carriers' Association and a combined loss of 194 "steaming days" (Lake Carriers' Association 1994).

The long, hard winter took its toll on the Coast Guard fleet. Several vessels suffered various mechanical difficulties, and the *Neah Bay* experienced an electrical fire. The *Mackinaw* sustained a broken crank shaft on one of her diesel engines. Commercial vessels also paid a price attempting to venture into ice areas unassisted. The *Golden Sky, George A. Stinson,* and *Algolake* sustained cracks in their bows. The *Algoway* and *Burns Harbor* had holes punched in their bows by ice, and the *Federal Danube* and the *Federal Thames* had less severe bow damage. For the first time in many years, the icebreaker *Mackinaw* employed the convoy system to escort vessels on Lake Superior (Table 4). Ironically, the severe winter may have extended the life of that ship, which had previously been slated for decommissioning due to funding shortages. Unprecedented cooperation between the United States and Canada aided in the process of keeping critical waterways usable. The Canadian polar icebreaker *Pierre Radisson* was brought into the lakes to help. The United States ordered the *Morro Bay* onto the lakes, but she was turned away enroute when the ice broke up quickly in mid-April.

6. Concluding remarks

Many of the economic impacts of a winter with much-above-average Great Lakes ice cover are noted above. The ecological impacts of a severe winter on the Great Lakes, however, are more difficult to assess because so few observations of Great Lakes physical characteristics, flora, and fauna are made when ice is present (during late autumn, winter, and early spring). Recent studies suggest that some of the affects of much-above-average ice cover on the Great Lakes winter ecosystem (due to increased stability in the underwater environment afforded by early ice formation and extensive ice cover) include lower over-winter mortality of whitefish eggs and the potential for a larger year class size (Brown et al. 1993; Taylor et al. 1987), higher diatom production

TABLE 5. Summary of Ninth District U.S. Coast Guard ice breaking and aircraft operations and value and amount of commercial ship cargo assisted for winters 1980–94 (Ninth District, USCG, 1995, personal communication). Vessel operations include direct assistance given to commercial vessels beset in the ice, U.S. Coast Guard vessel escorts of commercial ships through heavy ice fields, and U.S. Coast Guard vessel maintenance of tracks through ice fields and ship time logged for ice jams and flood relief operations in rivers and connecting channels of the Great Lakes.

	Vessel operations		Cargo			Aircraft
Year	No.	h	Tons	Barrels	Value ($)	h
1994	382	5757*	2 679 097	1 396 034	130,810,432	578*
1993	158	2543	772 475	715 009	73,677,252	381
1992	108	3107	387 990	442 300	37,505,820	350
1991	128	2498	13 852	795 000	70,021,440	225
1990	174	3556	3 513 440	989 283	158,628,868	61
1989	194	3204	1 287 489	812 965	195,160,337	74
1988	105	1267	719 708	450 757	47,778,863	94
1987	10	255	77 472	124 860	6,616,816	113
1986	160	1593	616 884	1 009 699	88,705,524	131
1985	131	765	817 863	336 796	75,383,482	140
1984	747	2900	5 513 017	127 213	474,539,582	273
1983	6	55	14 014	38 000	1,441,165	20
1982	145	2684	664 966	942 880	95,871,338	65
1981	195	1556	1 136 428	1 013 012	151,833,704	161
1980	115	850	710 319	1 138 315	81,955,299	199

*The hourly cost of various Ninth District U.S. Coast Guard resources for winter 1994 include the following: the USCC *Mackinaw* \$3322 h^{-1}, the buoy tender class vessels (WLB) \$1333 h^{-1}, the bay class ice breaking vessels (WTGB) \$939 h^{-1}, and aircraft (helicopters) \$3736 h^{-1}.

in ice-covered embayments (Vanderploeg et al. 1992), and a decrease in total phosphorus concentrations and suspended material in the water column the following spring and summer (Rockwell et al. 1980).

a. Winter 1994 ice conditions viewed from a historical perspective

The Laurentian Great Lakes, taken as a unit, developed one of its most extensive ice covers in over a decade during winter 1994. However, the likelihood of a future Great Lakes ice season similar to winter 1994 is difficult to assess because past frequency is not necessarily a good predictor of future frequency. Going by the past three decades, only winter 1979 had greater regional maximal ice cover; however, the winters of 1963, 1977, and 1982 also had much-above-average regional maximal ice covers (maximal regional ice cover in excess of 80%). In winter 1994, the extensive midlake ice covers during January and the seasonal maximal ice extent the first half of February were at least two weeks earlier than normal; the duration of extensive midlake ice cover (from the second half of January to early to mid-March) was two–four weeks longer than normal. Ice loss in the second half of March and the first half of April was slower than normal due to the large mass of ice formed during this severe winter and due to rafting of existing ice covers.

b. Normal ice cover viewed from a historical perspective

The "normal" seasonal progression of ice cover used here is derived from a climatic analysis of observed ice conditions, using over 2800 historical ice charts for winters from 1960 to 1979 (Assel et al. 1983). That ice cover climatology is placed in the historical perspective of the past 40 years by a one-dimensional ice thermodynamics model (Croley and Assel 1994), which indicates that decadal average ice covers for proceeding (1980–89) and preceding (1950–59) decades were less extensive than the ice cover for the 20-yr period of the ice cover climatology (1960–79). Trends in Great Lakes ice cover back to the late 1890s were investigated for Lakes Superior and Erie using air temperatures and ice cover models (Assel 1990). Reconstructed lake-averaged ice cover for Lakes Superior and Erie for the winters from 1898 to 1983 imply three ice-cover regimes relative to the 86-winter average: 1) a high ice-cover regime (more extensive ice cover) from the early 1900s to the mid-1920s,

Table 6. Ice-related lost steaming days, U.S. Flag Lakers, Spring 1994 (Lake Carriers' Association 1994). The *Alpena, J. A. W. Iglehart,* and *Paul H. Townsend* are cement carriers. All other ships are boom-type self-unloaders in the iron ore, coal, and stone trades. In addition to the lost steaming days, many vessels experienced much longer transit times once they were able to set sail. For example, it took the cement carriers *Alpena* and *J. A. W. Iglehart* 43 h to proceed the last 8 mi of their first voyage of the shipping season. The ore carriers *Edgar B. Speer* and *Arthur M. Anderson* are not included in the table, as they did begin service on their scheduled date (March 24), but what should have been a 24-h trip across Lake Superior became a 3-day convoy lead by the *Mackinaw.* (For sail dates, M=March, A=April.)

Vessel	Per-trip cargo capacity (gross tons)	Scheduled sail date	Actual sail date	Lost steaming days	Vessel	Per-trip cargo capacity (gross tons)	Scheduled sail date	Actual sail date	Lost steaming days
Charles M. Beeghly	31 000	M 23	A 08	16	*Reserve*	25 500	A 09	A 16	7
Herbert C. Jackson	24 800	M 24	A 05	12	*Armco*	25 500	M 31	A 07	7
American Mariner	31 770	M 16	M 28	12	*George A. Stinson*	59 000	M 24	M 30	6
Mesabi Miner	59 000	M 23	A 02	10	*Sam Laud*	23 407	A 06	A 12	6
Courtney Burton	22 425	A 02	A 12	10	*Columbia Star*	61 500	M 30	A 05	6
James R. Barker	59 000	M 23	A 01	9	*Lee A. Tregurtha*	29 100	M 24	M 29	5
Oglebay Norton	61 000	M 31	A 09	9	*American Republic*	24 270	M 23	M 28	5
William R. Roesch	19 700	A 12	A 21	9	*Wolverine*	19 700	A 02	A 07	5
Paul R. Tregurtha	61 000	M 22	M 30	8	*J. A. W. Iglehart*	12 300	M 18	M 22	4
Paul Thayer	19 700	A 05	A 13	8	*Wilfred Sykes*	21 500	M 15	M 18	3
Indiana Harbor	61 390	M 23	M 30	7	*Joseph L. Block*	37 200	M 16	M 19	3
St. Clair	39 560	M 24	M 31	7	*Alpena*	15 265	M 18	M 21	3
Walter J. McCarthy, Jr.	61 390	M 29	A 05	7	*Paul H. Townsend*	8400	M 17	M 19	2
John J. Boland	20 109	M 30	A 06	7	*Kaye E. Barker*	25 360	M 14	M 15	1
					Totals	**959 846**			**194**

2) a low ice-cover regime from the mid- to late 1920s to mid- to late 1950s, and 3) a second high ice-cover regime from the 1960s to the early 1980s. Thus, the "normal" ice cover used in this study is likely more similar to the first quarter of the twentieth century than to the intervening years through 1960.

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